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# Effect of Injection Molding Parameters on Shrinkage Behavior of Recyclable Polymers

**Ms. Sumaiya Benta Nasir, Grand Valley State University**

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## Abstract

This study investigates the effects of mold and melt temperatures on the shrinkage behavior of phone case injection molding simulations using five widely used recyclable plastic materials: HDPE, PP, TPV, ABS, and PC. A full factorial design of experiments (DOE) was employed, considering two critical factors, mold temperature and melt temperature, each at two levels. The simulations were conducted using Moldex3D software, with a complex geometry featuring varying thicknesses and hole sizes, designed in Solid Works. The analysis highlights the significant influence of material selection and process parameter optimization in achieving desired product quality. Among the tested materials, ABS exhibited the lowest shrinkage values, ranging from 1.96 mm to 7.43 mm, making it the most suitable choice for minimizing shrinkage in phone case production. ANOVA results revealed that both mold and melt temperatures significantly affect material shrinkage, with P-values of 0.033 and 0.003, respectively. While ABS demonstrated superior shrinkage control, other materials, including PP, PC, and TPV, showed higher shrinkage ranges but were similarly influenced by the process parameters. In contrast, HDPE exhibited the highest shrinkage variability and was less affected by these parameters. These findings emphasize the importance of selecting the appropriate material and controlling critical process parameters in plastic injection molding to achieve optimal product quality. Future research should explore additional variables, such as packing pressure, injection pressure, gate design, and a broader range of recyclable polymer materials, to further enhance understanding and control of shrinkage in injection molding.

## Introduction

Shrinkage is a critical factor in polymer manufacturing processes, particularly in injection molding, as it directly impacts the dimensional accuracy and performance of the final product. Various process parameters, including melt temperature and mold temperature, are known to influence shrinkage behavior, but their effects vary across different materials. Understanding these relationships is essential for optimizing process conditions, minimizing dimensional variability, and enhancing product quality.

This study investigates the influence of melt temperature and mold temperature on the shrinkage of five commonly used polymer materials: high-density polyethylene (HDPE), polypropylene (PP), thermoplastic vulcanizates (TPV), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) using injection molding Simulation of Moldex3D. These materials are widely used in industrial applications, ranging from automotive parts to consumer products, due to their versatility, mechanical properties, and cost-effectiveness.

By conducting a detailed analysis of variance (ANOVA) for each material, this research aims to identify the significance of these process parameters and highlight the material-specific factors contributing to shrinkage. The findings of this study will provide valuable insights for process optimization and material selection in polymer manufacturing, ensuring improved dimensional stability and product performance.

## Literature Review

**Importance of Mold Temperature and Melt Temperature**

Mold temperature and Melt Temperatures are very important injection molding parameters that greatly influence the properties of the plastic products in injection molding process. The quality of the final products is dependent on controlling these variables [1][2][3]. The cooling rate of the polymer materials is influenced by the mold temperature. Higher mold temperature makes the cooling rate slower which can give better crystalline structure and good mechanical strength but makes the product more brittle. Higher mold temperature also helps to get a better surface finish and lower residual stress but consumes more energy. [4]. On the other hand, lower mold temperature results in faster cooling which compromises the mechanical strength due to low crystalline structure and dimensional instability due to higher shrinkage. Lower mold temperature also can result in other types of defects such as incomplete filling, sink marks, and warpage.[3].

Melt temperature also plays a crucial role for the quality of the plastic product. How well the polymer can fill the mold cavity depends on the viscosity achieved through the melt temperature. Low melt temperature can create higher viscosity which ultimately results in incomplete filling, short shots and poor weld lines whereas high melt temperature can improve these qualities, but polymer's mechanical property will be degraded with increased shrinkage [3]. To maintain the quality of the parts, optimum mold temperature and melt temperatures are very crucial [4].

Sustainability in injection molding helps reduce environmental impact by minimizing waste, energy consumption, and emissions.[5][6] The use of recyclable materials in injection molding is particularly important as it supports a circular economy, where materials can be reused, reducing the need for new raw materials and decreasing landfill waste. This not only lowers production costs but also enhances the overall environmental footprint of manufacturing processes.[7][8][13] Recyclable materials contribute to a more sustainable, eco-friendly approach while meeting the growing demand for environmentally conscious products.

**Material Selection**

In this study, five recyclable materials have been selected which are widely used in industry. Each of the materials has some unique properties which make them the right choice for specific applications.

- High-density polyethylene (HDPE) is a good choice when products need to have strength, durability and resistance to chemicals [9].
- Polypropylene (PP) is mostly used for manufacturing parts for automotive industry and consumer goods due to it's good chemical resistance and affordability [10].
- Thermoplastic Vulcanizates (TPV) material offers good resistance to both chemical and heat. The material also has good flexibility. As a result, different automotive components like gaskets, seals, etc. are made using TPV [11] .
- Acrylonitrile Butadiene Styrene (ABS) is easy to process and very commonly used to produce parts for automobiles and electronics. This plastic is also very tough and impact resistant [4].
- Polycarbonate (PC) is a special type plastic with good optical transparency, thermal and impact resistance properties. They are widely used for lighting and eyewear lenses [12].

## Methodology

An iPhone cell phone cover with a length of 5.65 inches, a width of 2.79 inches, and a model thickness of 5.4 mm was used for the simulation.

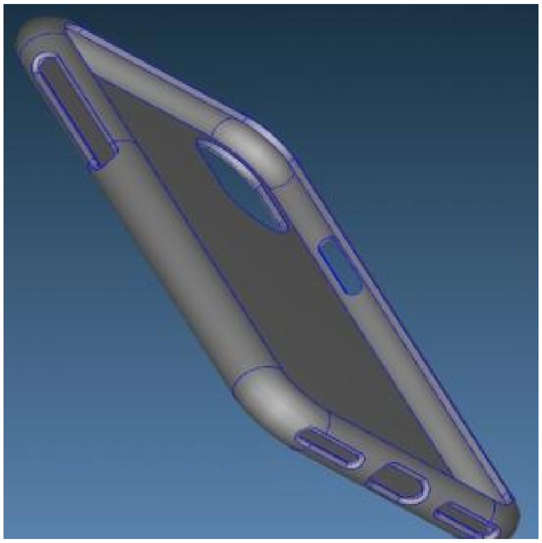

Figure 1: geometry of iPhone x case

## Simulation

In this study, a two-level full factorial Design of Experiments (DOE) analysis was conducted to evaluate shrinkage. Six recyclable materials—HDPE, PC, TPV, ABS, and PP—were used for the DOE. The injection molding process of an iPhone cell cover was simulated using Moldex3D.

Table 1: Recyclable material and their shrinkage

| Recyclable material | Melt temperature (degree Celsius) | Mold temperature (degree Celsius) | Shrinkage (mm) |
|---|---|---|---|
| HDPE | 40 | 200 | 7.68 |
| HDPE | 40 | 280 | 13.04 |
| HDPE | 80 | 200 | 11.37 |
| HDPE | 80 | 280 | 13.79 |
| PC | 40 | 200 | 3.54 |
| PC | 40 | 280 | 8.48 |
| PC | 80 | 200 | 4.01 |
| PC | 80 | 280 | 8.92 |
| TPV | 40 | 200 | 10.77 |
| TPV | 40 | 280 | 15.2 |
| TPV | 80 | 200 | 11.54 |
| TPV | 80 | 280 | 15.98 |
| ABS | 40 | 200 | 1.96 |
| ABS | 40 | 280 | 7.07 |
| ABS | 80 | 200 | 2.36 |
| ABS | 80 | 280 | 7.43 |
| PP | 40 | 200 | 4.18 |
| PP | 40 | 280 | 6.77 |
| PP | 80 | 200 | 4.75 |
| PP | 80 | 280 | 7.30 |

## Results and Discussion

### HDPE Material

The ANOVA results (Table 2) indicate that the model is not statistically significant (P-Value = 0.312), and neither melt temperature (P-Value = 0.372) nor mold temperature (P-Value = 0.230) significantly affects shrinkage. This suggests that the shrinkage of HDPE remains largely unaffected by the studied parameters under the given conditions. However, from the Adjusted sum of squares (Adj SS) for the model shows that mold temperature (15.132) has larger effect on shrinkage than the melt temperature (4.928).

Table 2: ANOVA (Analysis of Variance) of Shrinkage of HDPE material

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 2 | 20.060 | 10.030 | 4.64 | 0.312 |
| Linear | 2 | 20.060 | 10.030 | 4.64 | 0.312 |
| Melt Temperature | 1 | 4.928 | 4.928 | 2.28 | 0.372 |
| Mold Temperature | 1 | 15.132 | 15.132 | 7.00 | 0.230 |
| Error | 1 | 2.161 | 2.161 | | |
| Total | 3 | 22.221 | | | |

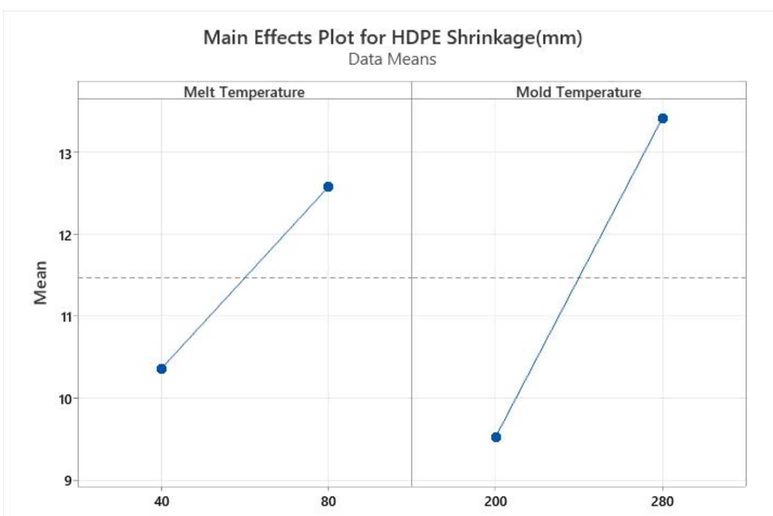


Figure-2: Main Effect Plot for HDPE Shrinkage (mm)

Main effect plot in Figure-2 shows that with increasing melt and mold temperatures, shrinkage increases with mold temperature. This plot also verifies the greater impact of mold temperature on the shrinkage of HDPE materials compared to melt temperature.

**PC Material**

The model for PC (Table 3) is highly significant (P-Value = 0.003). Both melt temperature (P-Value = 0.021) and mold temperature (P-Value = 0.002) significantly influence shrinkage, with mold temperature exerting the larger effect. These findings underscore the importance of precise mold temperature control for achieving dimensional accuracy in PP components.

Moreover, the Adjusted sum of squares (Adj SS) value for mold temperature (24.2556) is much higher than the Adj SS of melt temperature (0.2070) which means mold temperature greatly influence shrinkage compared to melt temperature.

Table 3: ANOVA (Analysis of Variance) of Shrinkage of PC material

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 2 | 24.4626 | 12.2313 | 54361.44 | 0.003 |
| Linear | 2 | 24.4626 | 12.2313 | 54361.44 | 0.003 |
| Melt Temperature | 1 | 0.2070 | 0.2070 | 920.11 | 0.021 |
| Mold Temperature | 1 | 24.2556 | 24.2556 | 107802.78 | 0.002 |
| Error | 1 | 0.0002 | 0.0002 | | |
| Total | 3 | 24.4629 | | | |

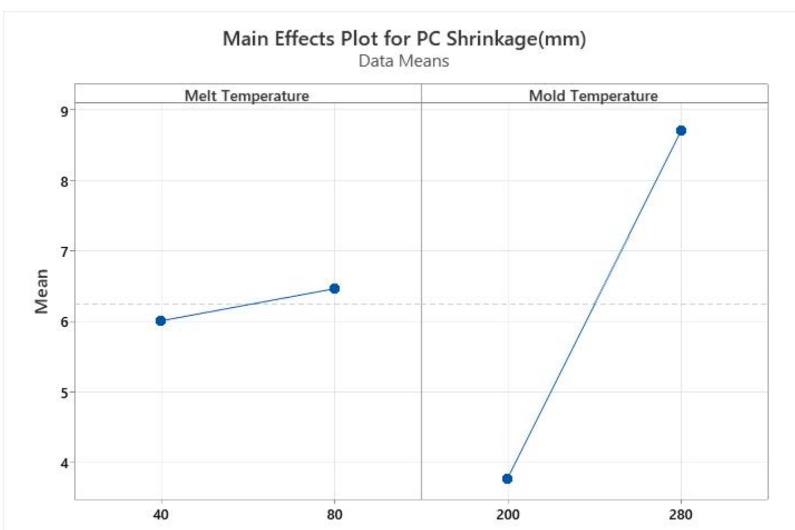


Figure-3: Main Effect Plot for PC Shrinkage (mm)

Main Effect Plot for PC Shrinkage (mm) in Figure-3 also shows that shrinkage increases greatly with increasing mold temperature. Shrinkage increases very slightly with increasing melt temperatures.

**TPV Material**

The model for TPV (Table 4) is highly significant (P-Value = 0.001), with both melt temperature (P-Value = 0.004) and mold temperature (P-Value = 0.001) significantly influencing shrinkage. Mold temperature is identified as the dominant factor, emphasizing its critical role in controlling shrinkage for TPV.

Like PP, the Adjusted sum of squares (Adj SS) value for mold temperature (19.6692) is higher than that for melt temperature (0.6006) which shows that mold temperature has larger effect on shrinkage compared to melt temperature. The Main Effect Plot for TPV Shrinkage in Figure-4 also shows the greater impact of mold temperature on shrinkage.

Table 4 : ANOVA (Analysis of Variance) of Shrinkage of **TPV** material

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 2 | 20.2699 | 10.1349 | 405397.00 | 0.001 |
| Linear | 2 | 20.2699 | 10.1349 | 405397.00 | 0.001 |
| Melt Temperature | 1 | 0.6006 | 0.6006 | 24025.00 | 0.004 |
| Mold Temperature | 1 | 19.6692 | 19.6692 | 786769.00 | 0.001 |
| Error | 1 | 0.0000 | 0.0000 | | |
| Total | 3 | 20.2699 | | | |

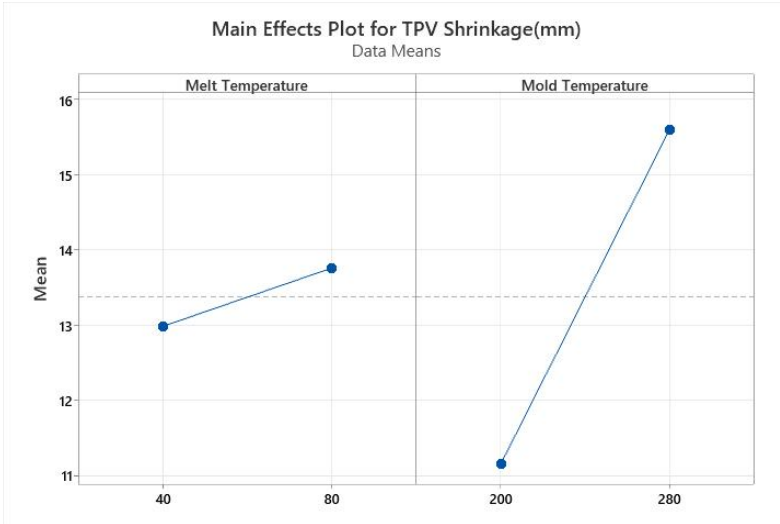


Figure-4: Main Effect Plot for TPV Shrinkage (mm)

**ABS Material**

The ANOVA results for ABS (Table 5) show a highly significant model (P-Value = 0.004). Both melt temperature (P-Value = 0.033) and mold temperature (P-Value = 0.003) are significant factors, with mold temperature having the greatest impact. This highlights the necessity of maintaining strict mold temperature control for dimensional stability in ABS parts.

The Adjusted sum of squares (Adj SS) value of Mold temperature (25.9081) is much larger than that of melt temperature (0.1444) which shows that mold temperature has larger influence on shrinkage compared to melt temperature. Similar to PC and TPV materials, The Main Effect Plot for TPV Shrinkage in Figure-5 shows the greater impact of mold temperature on shrinkage.

Table 5: ANOVA (Analysis of Variance) of Shrinkage of ABS material

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 2 | 26.0525 | 13.0262 | 32565.63 | 0.004 |
| Linear | 2 | 26.0525 | 13.0262 | 32565.63 | 0.004 |
| Melt Temperature | 1 | 0.1444 | 0.1444 | 361.00 | 0.033 |
| Mold Temperature | 1 | 25.9081 | 25.9081 | 64770.25 | 0.003 |
| Error | 1 | 0.0004 | 0.0004 | | |
| Total | 3 | 26.0529 | | | |

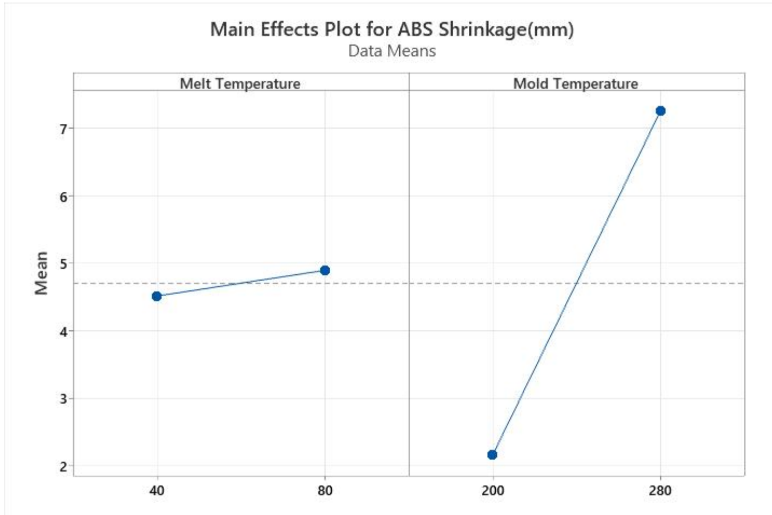


Figure-5: Main Effect Plot for ABS Shrinkage (mm)

**PP Material**

Table 6 shows that the model is highly significant (P-Value = 0.008). Both melt temperature (P-Value = 0.023) and mold temperature (P-Value = 0.005) are significant contributors to shrinkage, with mold temperature being the dominant factor. These results reaffirm the sensitivity of PP shrinkage to mold temperature variations.

Like above four polymer materials, The Adjusted sum of squares (Adj SS) value of Mold temperature (6.6049) is larger than that of melt temperature (0.3025) which indicates mold temperature having larger influence on shrinkage compared to melt temperature. We can also see the larger impact of mold temperature on shrinkage of PP material from the Main Effect Plot for PP Shrinkage in Figure-6.

Table 6: ANOVA (Analysis of Variance) of Shrinkage of PP material

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 2 | 6.90740 | 3.45370 | 8634.25 | 0.008 |
| Linear | 2 | 6.90740 | 3.45370 | 8634.25 | 0.008 |
| Melt Temperature | 1 | 0.30250 | 0.30250 | 756.25 | 0.023 |
| Mold Temperature | 1 | 6.60490 | 6.60490 | 16512.25 | 0.005 |
| Error | 1 | 0.00040 | 0.00040 | | |
| Total | 3 | 6.90780 | | | |

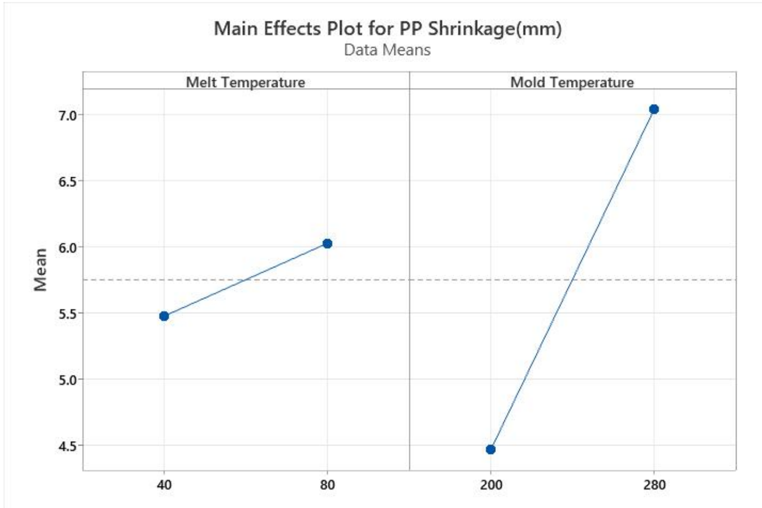


Figure-6: Main Effect Plot for PP Shrinkage (mm)

Table 1 shows that HDPE has a shrinkage range of 7.68 to 13.79 mm, PC ranges from 3.54 to 8.92 mm, TPV from 10.77 to 15.98 mm, ABS from 1.96 to 7.43 mm, and PP from 4.18 to 7.30 mm.

ABS has the lowest shrinkage values across all conditions, with a minimum shrinkage of 1.96 mm and a maximum of 7.43 mm.

Moreover, the ANOVA test results show that the shrinkage of ABS materials are significantly influenced by both melt temperature (P value 0.033) and mold temperature (P value 0.003). Melt and mold temperatures are the significant parameters to achieve the required product quality which is the lowest shrinkage. However, from the Adjusted Sum of Square (Adj SS) values, we understand that mold temperature has greater influence on shrinkage compared to the melt temperature.

In this research, only molding and melt temperatures were considered as the key parameters due to the high computational time required for the simulations. The complexity of the injection molding process means that including a wider range of parameters would have significantly increased the simulation time. However, there are several other factors that can influence the injection molding process. In future studies, it would be beneficial to include parameters such as injection pressure, filling time, packing pressure, cooling time, gate size, gate locations, cooling channel number, and orientations. These factors play important roles in material flow, cooling rates, and part quality, and their inclusion could provide a more comprehensive understanding of the molding process

In this study, a two-level full factorial Design of Experiments (DOE) was conducted to analyze the effect of melt temperature and mold temperature on the shrinkage of recyclable plastics using Moldex3D simulation. One key limitation of this study is that the simulation was deterministic, meaning each combination of process parameters produced a single shrinkage value without variation. In physical experiments, multiple replications introduce natural variability, allowing for a meaningful error term in ANOVA calculations. However, in this study, because each condition was tested only once, the within-group variance is effectively zero, making the F-tests and p-values unreliable.To improve the statistical validity of ANOVA in future studies, multiple simulations should be conducted per test condition, introducing slight variations such as mesh refinement or solver settings to create a meaningful error term. While ANOVA was conducted in this study, the deterministic nature of the simulation limits the reliability of p-values and F-tests. Future research should incorporate multiple simulation replications for valid statistical inference.

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## Conclusion

This study analyzed the effects of mold and melt temperatures on the shrinkage behavior of phone case injection molding simulations using five commonly used recyclable plastic materials: HDPE, PP, TPV, ABS, and PC. The findings highlight the critical role of material selection and process parameter control in achieving optimal product quality in plastic manufacturing. Among the materials studied, ABS demonstrated the lowest shrinkage values, ranging from 1.96 mm to 7.43 mm, making it the most suitable choice for minimizing shrinkage in phone case production. ANOVA test results confirmed that both melt and mold temperatures significantly influence shrinkage, as indicated by P-values of 0.033 and 0.003, respectively.

While ABS showed the minimum shrinkage values, other materials such as PP, TPV, and PC exhibited higher shrinkage ranges but were similarly affected by the process parameters. In contrast, HDPE demonstrated high shrinkage variability and was relatively less affected by melt and mold temperatures.

These results underscore the importance of selecting appropriate materials and optimizing critical parameters to ensure product quality in plastic injection molding. Future studies should expand on these findings by investigating additional process variables such as packing pressure, injection pressure, gate size and location, and by incorporating a wider variety of recyclable polymer materials. This broader scope would provide a more comprehensive understanding of the factors influencing shrinkage and overall product quality in injection molding processes.

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